**LUNAR SOIL EROSION PHYSICS FOR LANDING ROCKETS ON THE MOON.** Ryan N. Clegg[1], Philip T. Metzger[2], Stephen Huff[2], and Luke B. Roberson[2], [1]Washington University in St. Louis, Department of Earth and Planetary Sciences, 1 Brookings Drive, St. Louis, MO 63130, USA, rclegg@levee.wustl.edu [2]NASA Kennedy Space Center, Mail Code KT-D-3, Kennedy Space Center, Florida, 32899, USA, Philip.T.Metzger@nasa.gov or Luke.B.Roberson@nasa.gov.

**Introduction:** For future lunar operations, we must understand the blowing of soil during launch and landing of spacecraft. For example, the Apollo 12 Lunar Module landed approximately 160 meters from the deactivated Surveyor III spacecraft, scouring its surfaces and creating numerous tiny pits. Based on simulations and video analysis from the Apollo missions, blowing lunar soil particles have velocities up to 3000 m/s at low ejection angles relative to the horizon, reach an apogee higher than the orbiting Command and Service Module, and travel nearly the circumference of the Moon [1-3, 6]. The low ejection angle and high velocity of blowing soil particles are concerns for instruments deployed on the Moon, as well as for the historic Apollo landing sites. Deployed instruments would be sandblasted if another lander lands nearby. Hardware could also be damaged by "hopper" landers such as those being designed by some of the Google Lunar X-Prize teams. These landers would land, then "hop" to another location using rockets that would disturb the lunar soil. With the X-Prize Landers also potentially landing near the historic Apollo sites, the need arises to develop rules and practices in order to prevent damage to the Lunar Modules and to any experiments or debris left by astronauts. Apollo sites are valuable as witness plates to the lunar and inner solar system environments and therefore must be protected. Debris left by the astronauts is of value to astrobiologists, to study and determine if and how any strains of microorganisms survived over the past 40 years in the lunar environment. Contamination by blowing soil from rocket landings would hinder any chances of obtaining this valuable science.

**Experimental:** As a first step in investigating this concern, we have performed a series of low-velocity impact experiments in a modified sandblasting hood using lunar soil simulant (JSC-1A) impacted upon various materials that are commonly used in spaceflight hardware. The impacted materials include glass, gold foil blankets, multi-layer insulation (MLI) for cryogenic tanks, and several textiles that are under consideration for building a blast barrier around lunar landing pads.

*Velocity Calibration.* The velocities of individual soil particles of different diameters were calibrated with a high-speed video camera that recorded their trajectories through the chamber. Their velocities were in the range of 30-85 m/s, depending on the particle size and the experiment settings. This is much slower than will occur in a lunar landing. However, even in the lunar case the impacts are not hyper velocity and so the resulting damage can be compared through the Sheldon-Kanhere equation [5],

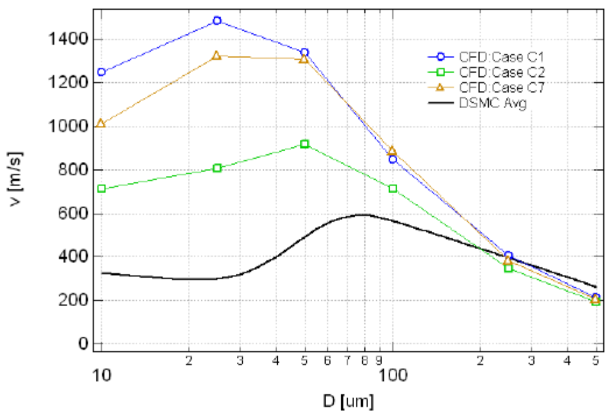


Figure 1: Particle speeds exiting a CFD boundary for various particle sizes [4]. Black line is averaged values from [1].

$$V = K_D v^3 D^3 \sigma^{3/2} H_V^{-3/2}$$

which predicts the volume $V$ of a pit caused by a single impacting particle of diameter $D$ and velocity $v$, when the particle has a material density $\sigma$ and the target material has a Vicker's hardness value $H_V$. ($K_D$ is related to the angle of impact on the target.) We integrated this equation across the particle size and the velocity distributions as determined by [1] for lunar soil in actual landings and also for JSC-1A in our experiment. Taking the ratio of these (or similar) integrals, the material parameters cancel out and we determine what quantity of lunar simulant will produce the same total volume (or surface area) of pitting in the target to simulate a specified number of lunar landings.

*Lunar Simulation.* We applied this methodology to simulate the same area and volume of pitting damage as experienced by Surveyor III. We exposed five different sheets of glass to the equivalent of between one and five lunar landings at 200 m distance. After one landing equivalent of spray, the glass was severely eroded and unusable. Thermal control gold foil blankets exposed to this spray lost all of their gold coating. Candidate materials that may be used as a lunar fence impact barrier [3] were blasted with 1 landing equivalent of JSC-1A. As shown in Figure 2, Kevlar (A) experienced surface erosion. Woven carbon fiber samples (B) and hybrid Kevlar-carbon fiber (C) failed. Vectra fabric (B), used in the Mars rover balloons, showed no significant impact damage.

*Figure 2*: Carbon Fiber (A), Kevlar (B), Hybrid (C), and Vectra (D) textiles after exposure to lunar simulant spray.

**Further Work:** On-going work is verifying the predictions of the Sheldon-Kanhere equation and quantifying the damage that lunar hardware would experience. We also plan to functionally test thermal control blankets for loss of reflectivity and solar cells for loss of received power. Future work must also include impacts at realistic lunar velocities at an appropriate NASA facility.

**References:** [1] Lane, John E., et al (2008), "Lagrangian trajectory modeling of lunar dust particles," *Earth and Space 2008* (Long Beach, California). [2] Immer, Christopher D., et al (2008), "Apollo Video Photogrammetry Estimation of Plume Impingement Effects," *Earth and Space 2008* (Long Beach, California). [3] Metzger, Philip T., et al. (2008), "Modification of Roberts' theory for rocket exhaust plumes eroding lunar soil," *Earth and Space 2008* (Long Beach, California). [4] Lane, John E., et. al, "Lunar Dust Particles Blown By Lander Engine Exhaust in Rarefield and Compressible Flow" [5] Sheldon and Kanhere (1972), "An Investigation of Impingement Erosion Using Single Particles," *Wear* **21**, 195-209. [6] Morris, A.B., et. al (2010), "Plume Impingement on a Dusty Surface," *27th International Symposium on Rarefied Gas Dynamics* (Asilomar, California).